Electron Cooling for Low-energy RHIC operation

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2012 RHIC & AGS Users' Meeting
June 12-15, 2012

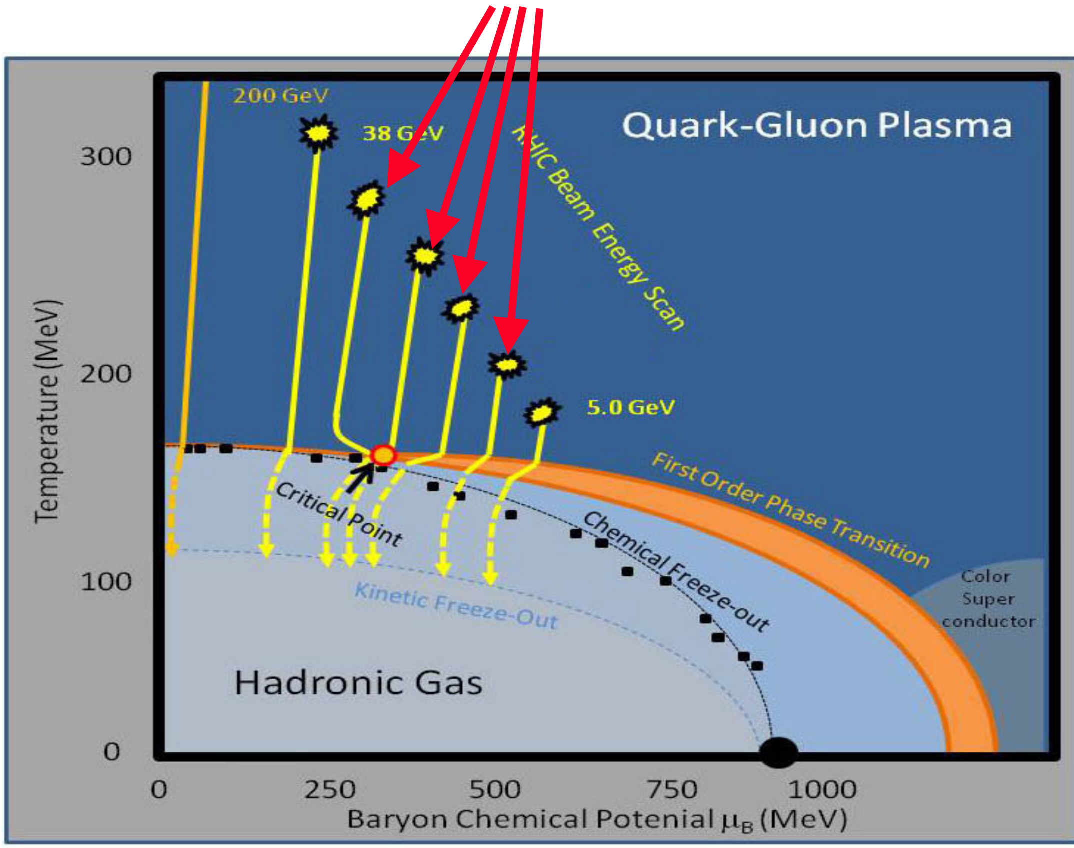
Low-Energy RHIC program:

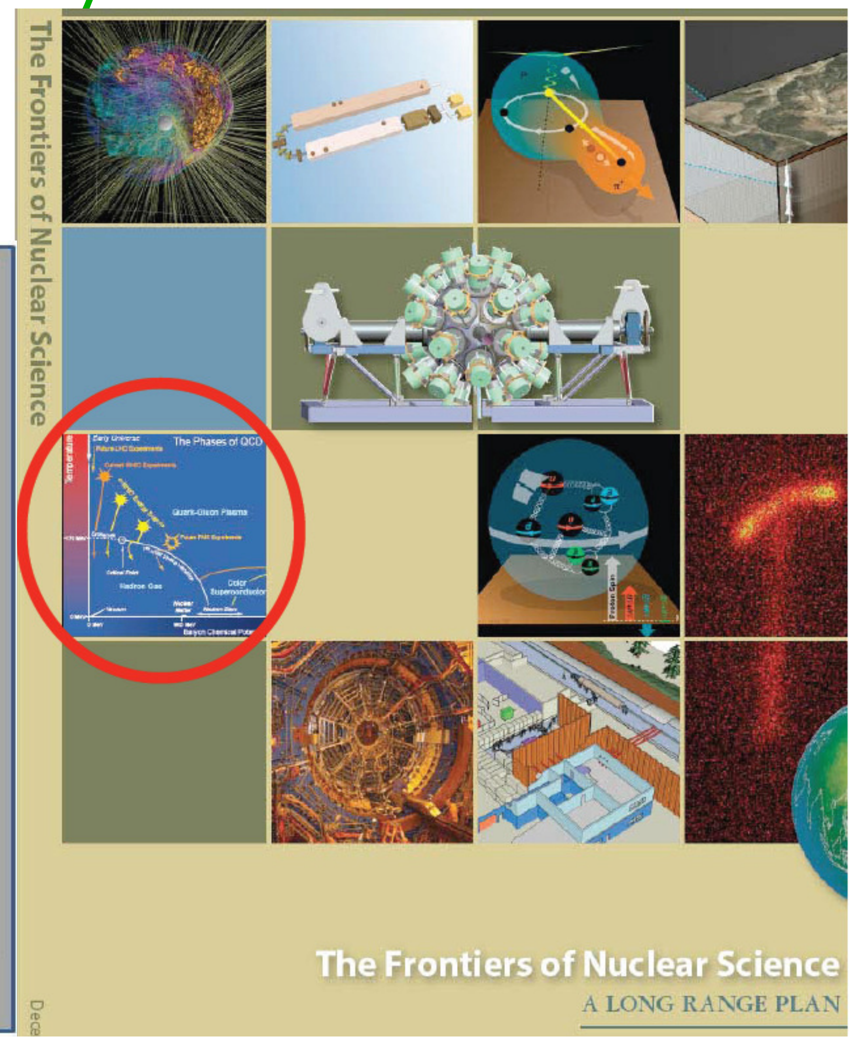
Operation with heavy ions to search for QCD phase transition Critical Point.

Low-Energy scan, c.m. energies:

$\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 18, 27 GeV/n

(2010 & 2011 RHIC runs)





Low-energy RHIC operation

Electron cooling (method of increasing phase-space density of hadron beams):

- "cold" electron beam is merged with ion beam which is cooled through Coulomb interactions
- electron beam is renewed and velocity spread of ion beam is reduced in all three planes.

requires co-propagating electron beam with the same average velocity as velocity of hadron beam.

Energy scan of interest:

$\sqrt{s_{NN}}$ = 5, 6.3, 7.6, 8.6, 12, 16, 20 GeV

E-cooler: $E_{e,kinetic}$=0.86-2.8 MeV

$E_{e,kinetic}$=1.8 MeV cooler

At low energies in RHIC luminosity has a very fast drop with energy (from γ^3 to γ^6). As a result, achievable luminosity becomes extremely low for lowest energy points of interest.

However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

To extend cooling up to 20 GeV c.m. energies one needs 4.9 MeV electron cooler.

Beam dynamics luminosity limits for RHIC operation at low energies

Some fundamental limitations come from:

Intra-beam Scattering (IBS):

- **Strong IBS growth at lowest energies- can be counteracted by Electron cooling**

Beam-beam:

- **Becomes significant limitation for RHIC parameters only at $\gamma > 20$.**

Space charge:

- **At lowest energies, ultimate limitation on achievable ion beam peak current is expected to be given by space-charge effects.**

Luminosity limitation by space-charge and beam-beam

Luminosity expressed through

beam-beam parameter ξ:

$$L = \frac{A}{Z^2 r_p}\frac{N_i c}{\beta^* C}\frac{2\gamma\beta^3}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

$$\xi = \Delta Q_{bb} = -\frac{Z^2 r_p}{A}\frac{N_i}{4\pi\beta^2\gamma\varepsilon}\frac{1+\beta^2}{2}$$

Luminosity expressed through

space-charge tune shift ΔQ_{sc}:

$$L = \frac{A}{Z^2 r_p}\frac{N_i c}{\beta^*}\frac{\sqrt{2\pi}\sigma_s}{C^2}\gamma^3\beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q_{sc}$$

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A}\frac{N_i}{4\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f}$$

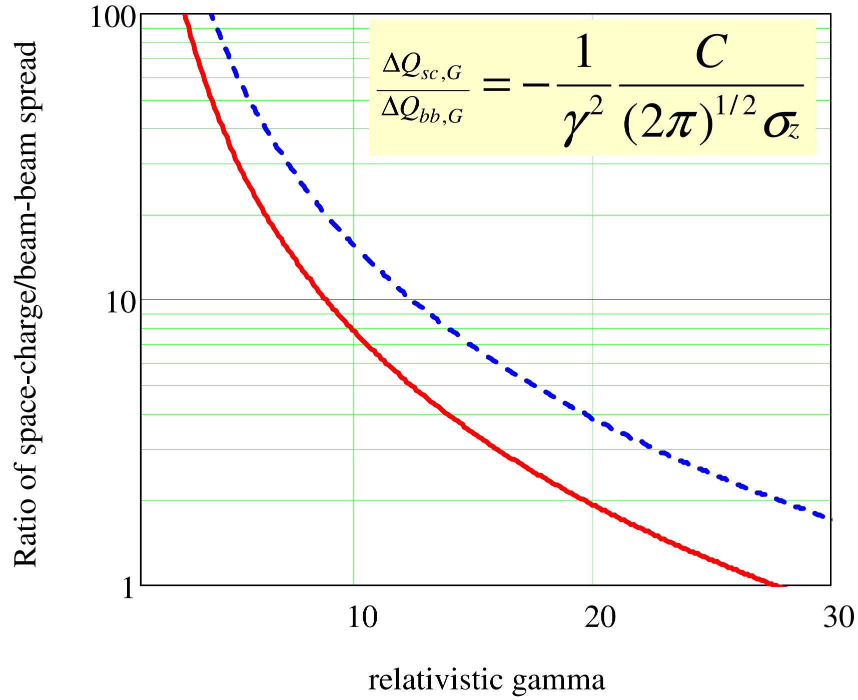
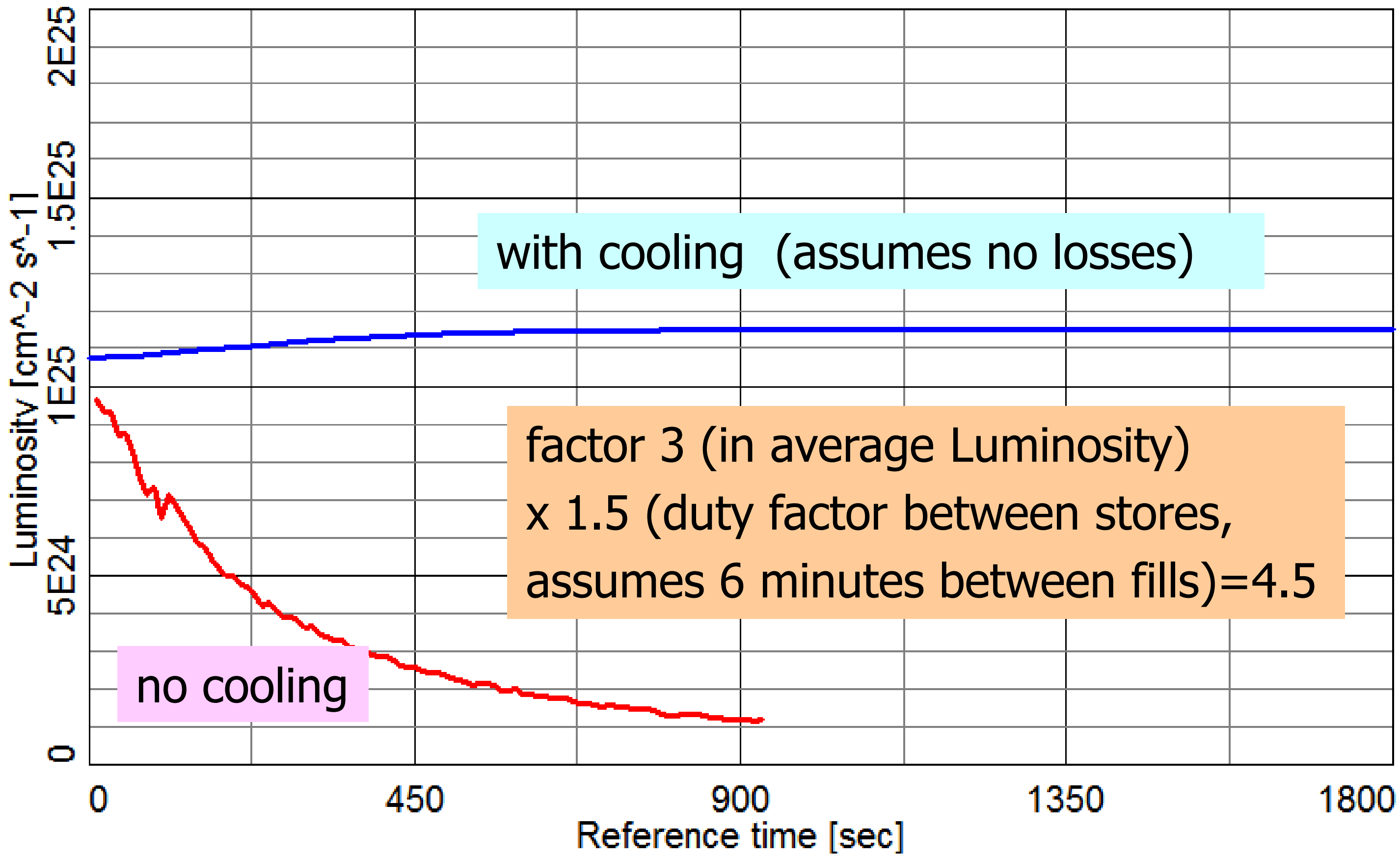


Figure 1: Ratio of space-charge tune spread to beam-beam spread (for heavy ions) at low energies in RHIC for rms bunch length 2 m (red) and 1 m (blue, upper dash line).

Cooling of bunches with nominal length (1-2 m rms) (counteracting IBS only and longer stores)

Simulation of luminosity with electron cooling at beam energy of 3.85 GeV/n ($\sqrt{s_{NN}}$ =7.7 GeV).



Electron cooling benefits for nominal bunch length

1. Electron cooling should provide significant luminosity improvement for low-energy RHIC operation:

- $\sqrt{s_{NN}}$ < 11 GeV : factor 3-6

(*to get improvement from cooling below 7 GeV, need to establish stable RHIC operation with good beam lifetime first !)

test run: June 25-27, 2012

- $\sqrt{s_{NN}}$ =11-16 GeV: about factor of 6
- $\sqrt{s_{NN}}$ =16-20 GeV: factor 6-10*

(*additional factor at higher energies comes from cooling of transverse emittance to the space charge limit and decrease of β^*)

At least factor of 3-6 gain in luminosity for all low energies with nominal bunch length (1-2 m rms, 28 MHz RF).

2. Electron cooling offers longer stores with relatively constant luminosity.
3. Choice of a cooler with electron energy up to 5 MeV will extend cooling all the way up to present nominal injection energy with heavy ions. As such, if needed, pre-cooling of transverse and/or longitudinal emittance can be done for high-energy program as well.

Luminosity improvement with longer bunches

Additional gain in luminosity is possible if one can tolerate operation with longer bunches (9MHz RF) for lowest energies:

Since we are limited by space-charge tune shift, we cannot cool transverse emittance at lowest energy points of interest ($\sqrt{s_{NN}} < 11$ GeV).

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{C_r}{\sqrt{2\pi}\sigma_s}$$

However, if bunch length is relaxed, we can now cool transverse emittance which in turn allows to reduce β*. Losses on transverse acceptance will be minimized as well.

BNL C-AD Tech Note C-A/AP/449 (February 2012).

Luminosity limitation by space charge

$$L = \frac{N_i^2}{4\pi\varepsilon\beta^*} F_{coll} f\left(\frac{\sigma_s}{\beta^*}\right)$$

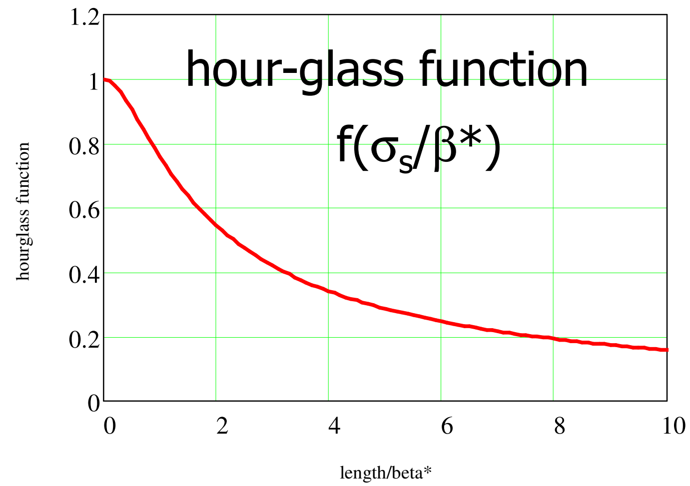
Luminosity expressed through space-charge tune shift ΔQ_{sc}:

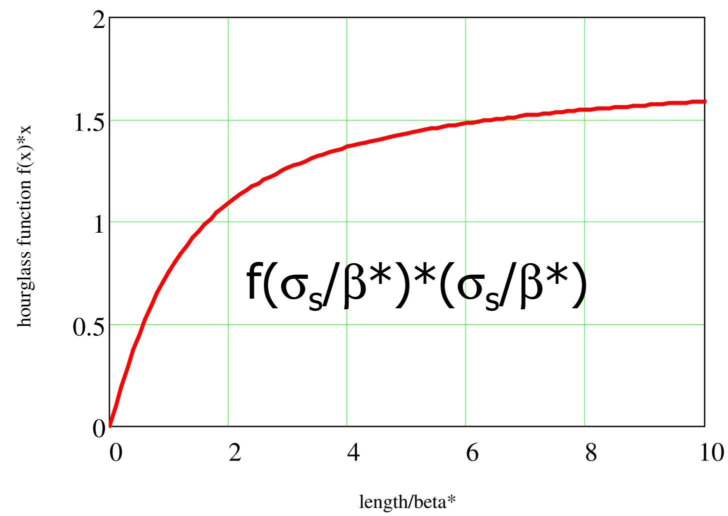
$$L = \frac{A}{Z^2 r_p} \frac{\sqrt{2\pi} N_i c}{C_r^2} \gamma^3 \beta^3 \frac{\sigma_s}{\beta^*} f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q_{sc}$$

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{C_r}{\sqrt{2\pi}\sigma_s}$$

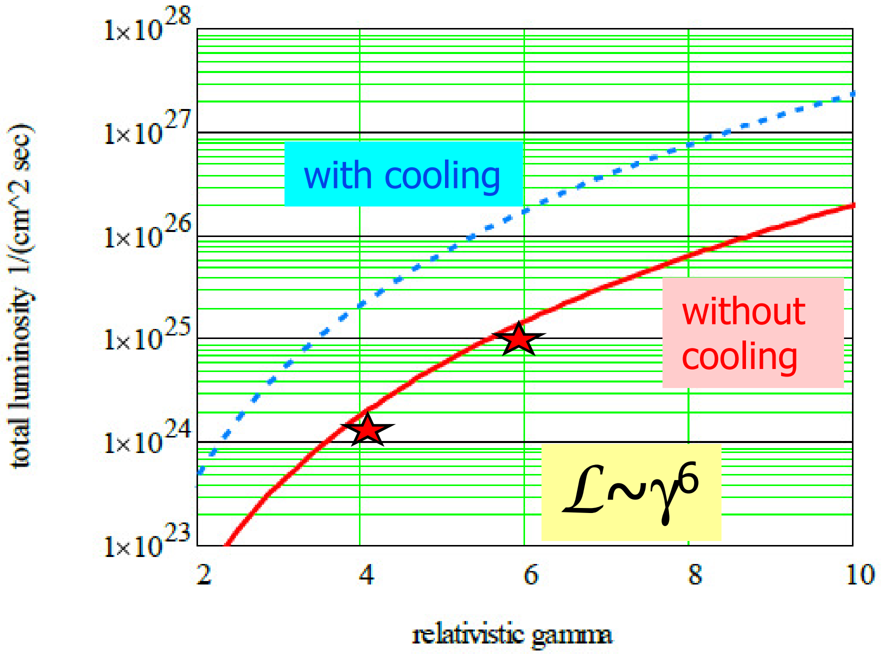
When also limited by transverse acceptance (which is the case for RHIC lowest energy points):

$$L = 8\pi^2 \left(\frac{A}{Z^2 r_p}\right)^2 \frac{c\varepsilon}{\beta^*} \frac{\sigma_s^2}{C_r^3} \gamma^6 \beta^5 f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q_{sc}^2$$





Projection (ideal) for luminosity improvement



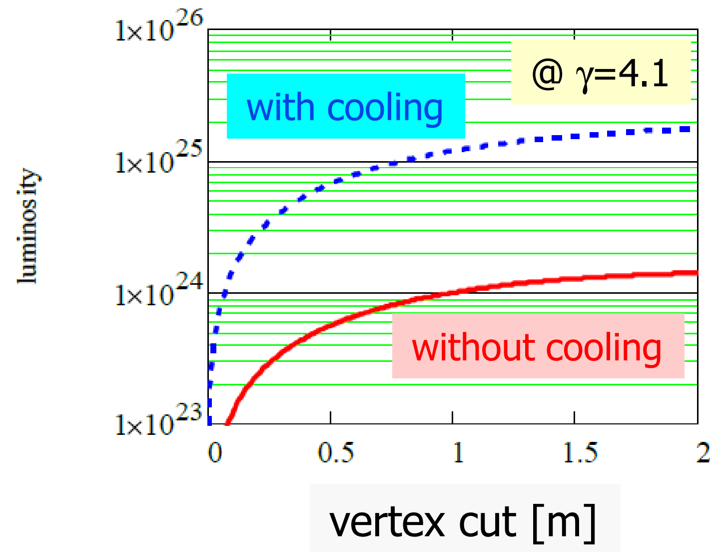


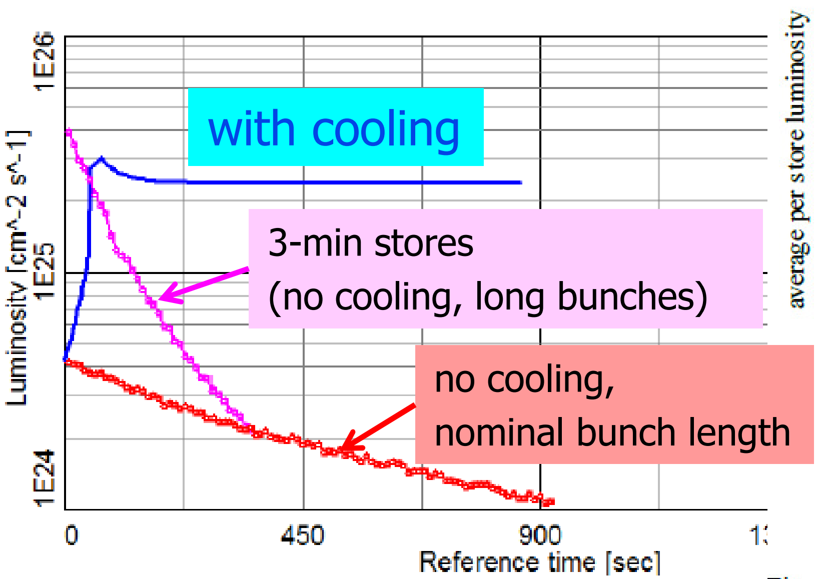
Fig. 6. Average luminosity for 111 bunches of Au ions in RHIC at γ=4.1

Fig. 8. Projection of total (without vertex cut) luminosity for 111 bunches of Au ions in RHIC for the space-charge tune spread of ΔQ_{sc}=0.05 with electron cooling and long bunches (blue, dash upper curve) and without cooling (red, solid lower curve).

Up to about factor of 10 gain in total luminosity for all low energies with longer bunch length may be expected from electron cooling (*although electron cooling is well established technique it was never done in a collider; exact factor of luminosity improvement will depend on optimization between cooling and beam lifetime).

Luminosity lifetime

Example for γ=4.1 ($\sqrt{s_{NN}}$ = 7.7 GeV):



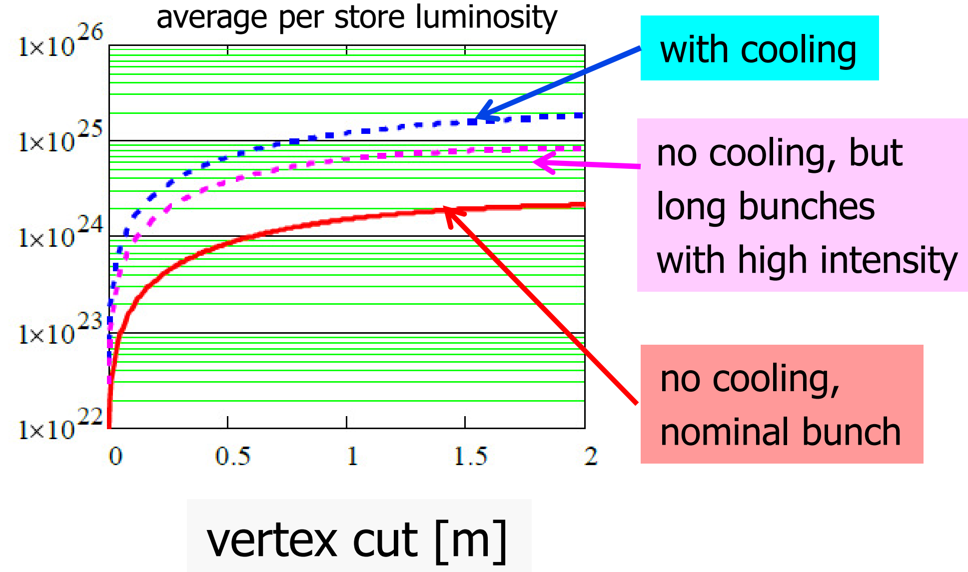


Fig. 9. Average (per store) luminosity for 111 bunches of Au ions in RHIC at γ=4.1

Fig. 10. Simulated luminosity evolution for 3 cases summarized in Fig. 9: 1) electron cooling and long bunches (σ_s=4.5 m, β^*=2 m, $\varepsilon_{n,95\%}$=5 μm, N_i=5e8) – blue, top curve; 2) without cooling (σ_s=1.5 m, β^*=6 m, $\varepsilon_{n,95\%}$=15 μm, N_i=5e8) – red; 3) without cooling but longer bunches with higher bunch intensity (σ_s=4.5 m, β^*=6 m, $\varepsilon_{n,95\%}$=15 μm, N_i=1.5e9) – magenta.

Electron cooler for Low-Energy RHIC

Different approaches are possible:

1. DC accelerator (Pelletron is available from FNAL since October 2011) –
   suitable for cooling: < $\sqrt{s_{NN}}$ =20 GeV:
   requires ~ 4 years from the start of the project with full commitment of needed resources from C-AD.

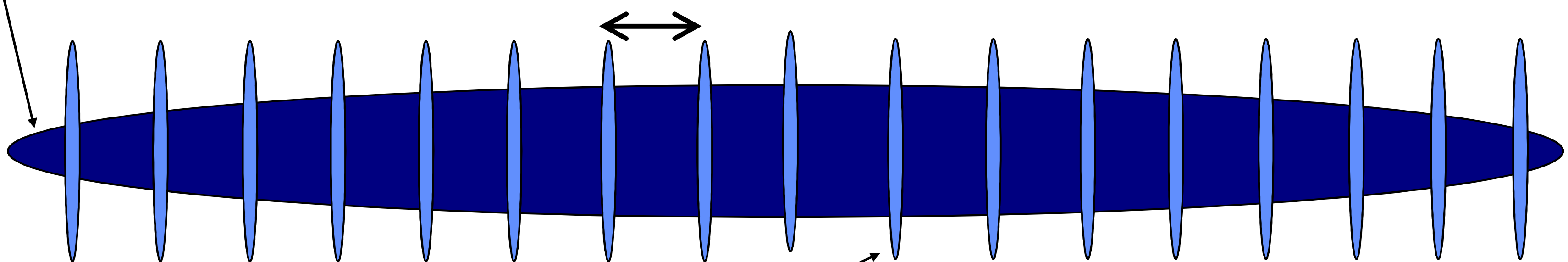
BNL C-AD Tech Note C-A/AP/307 (April 2008)

2. RF-gun bunched beam electron cooler.
   Several approaches possible:
   703 MHz BNL's ERL gun – cooling by a train of electron bunches
   56 or 112 MHz SRF gun – requires new SRF gun, challenging beam parameters
   can be designed to go above $\sqrt{s_{NN}}$ =20 GeV (putting ERL inside RHIC tunnel) as well:
   some R&D involved; cooling with bunched electron beams was never demonstrated.

RF gun approach using 703 MHz SRF gun of R&D ERL - under commissioning at C-AD

Ion bunch full bucket: length ~ 10 m (28 MHz RF)

42.61 cm

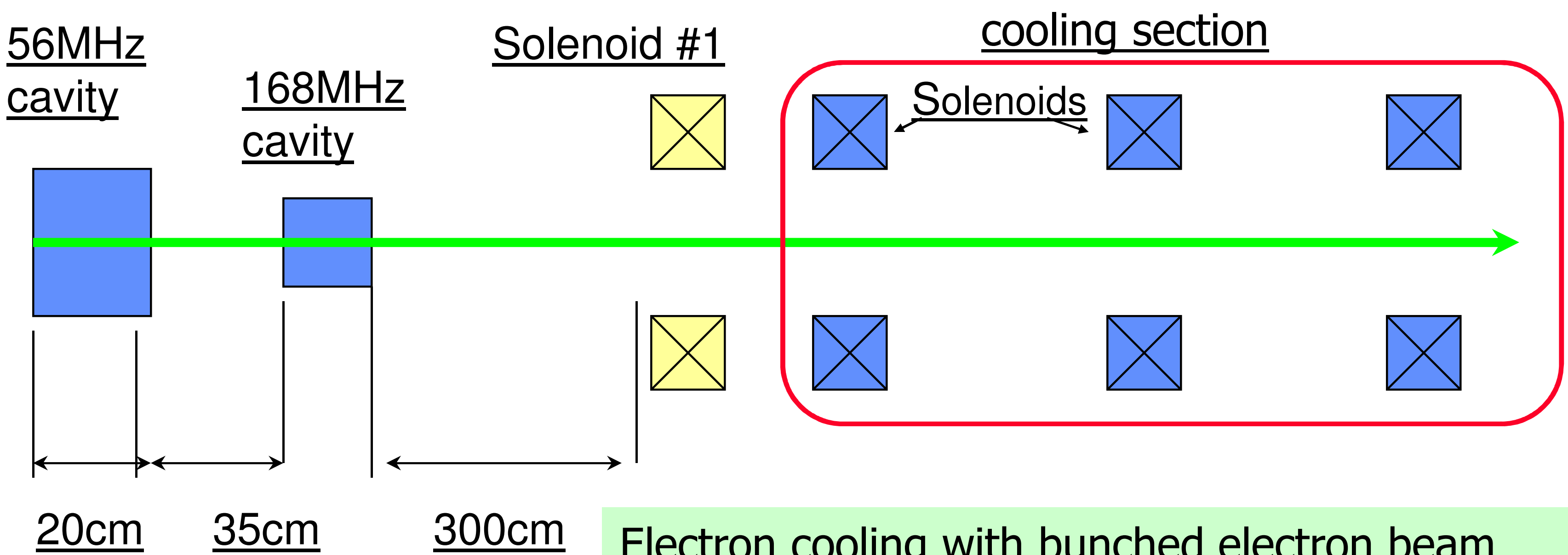


40 electron bunches:

charge per e-bunch 50 pC , electron bunches are 42.61 cm apart

First electron beam current from BNL's 703 MHz SRF gun is expected in 2012**.**

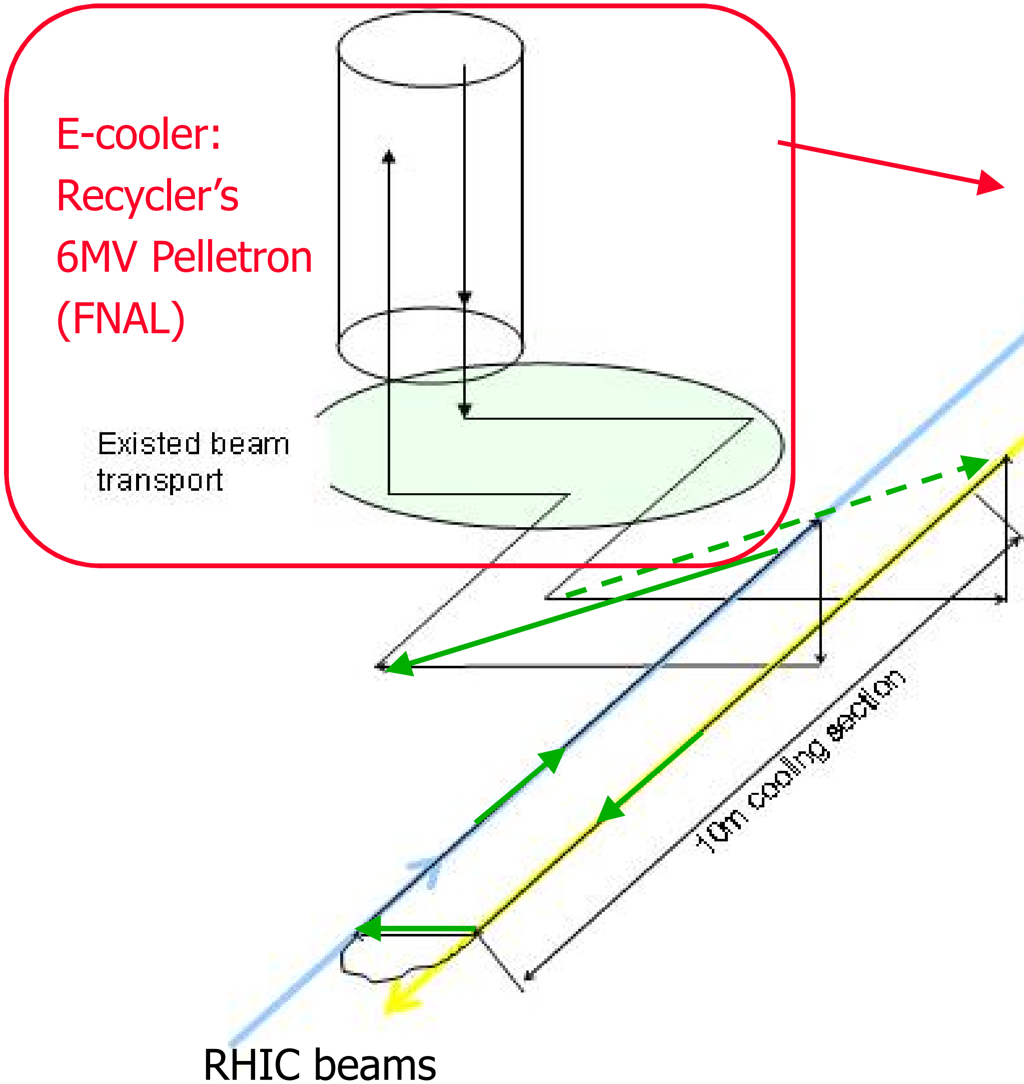
Possible configuration of electron cooler (based on 56 or 112 MHz SRF gun)



Electron cooling with bunched electron beam produced by 56 MHz gun – long bunch is needed to minimize space-charge effect in beam transport at low-energies.

Requires new SRF gun.

Possible Low-Energy RHIC DC electron cooler



Feasibility study showed that FNAL's Pelletron is well suited for low-energy cooling in RHIC.

Some challenges for e-cooling in a collider

Both technical and beam dynamics:

- **Operation in a wide range of energies; control of electron angles in cooling section for all energies.**
- **Use the same electron beam to cool ions in two collider rings; preserving beam quality from one cooling section to another.**
- **Suppression of recombination; effects on cooling.**

Cooling in a collider:

- **Control of ion beam distribution. Do not overcool beam core.**
- **Effects on hadron beam.**
- **Interplay of space-charge and beam-beam in hadrons.**

Summary

1. **Electron cooling can provide significant luminosity improvement for low-energy RHIC operation.**
2. **Electron cooling offers longer stores with relatively constant luminosity.**
3. **Minimizes beam loss and thus helps with possible radiation issues at low-energy RHIC operation.**
4. **Additional improvement with cooling might be possible if one can operate with larger space-charge tune shifts or apply space-charge compensation.**
5. **Choice of a cooler with electron energy up to 5 MeV will extend cooling all the way up to present injection energy with heavy ions. As such, if needed, pre-cooling of transverse and/or longitudinal emittance can be done for high-energy program as well.**

- **Implementation of electron cooling for RHIC operation at low energies requires about 4 years from the engineering start of the project:**

  Example: start of the project in October of 2012 should allow to start installation in 2014 with luminosity improvement in 2016-2017.

Thank you.